A DETERMINATION OF THE CHARACTERISTICS OF CEPHEIDS FROM B-TYPE COMPANIONS

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Photometry (*uvbyβ*) of five cepheids with B-type companions has been utilized to derive the spectral types and apparent magnitudes of the companions. By utilizing the period-luminosity relation it is possible to estimate the absolute magnitudes of the companions since the differences in magnitude between the companions and cepheids are known. The spectral types and absolute magnitudes of the B-type components indicate they are all evolved from the zero-age main sequence. By utilizing the ages of the B stars we can derive the ages of the cepheids under the assumptions that both stars of a binary were formed at the same time and the cepheids are more evolved than their B components. A period-age relation of the form $\log t_{age} = 8.60 - 0.83 \log P$ is found. Minimum masses of the cepheids can also be estimated from the data. No evidence of large mass loss is evident in the intermediate-band photometry of cepheids.

Pulsating variables, in particular classical cepheids, have played a central role in astronomy since the discovery of the period-luminosity (P-L) relation by Leavitt (1908, 1912). This relation has been a powerful tool for investigating astronomical distances. Today astronomers also find these stars to be useful tools for testing theories of stellar pulsation, structure, and evolution.

The greater part of the observational data available for studying cepheids is photometric (Mitchell et al. 1964; Wisniewski and Johnson 1968; Fernie and Hube 1968; Pel 1976; McNamara and Feltz 1980). A close examination of the photometry (Madore 1977), particularly where U observations are available, indicates that high-quality photoelectric photometry is capable of showing that a considerable number of cepheids have B-type companions. In fact, Madore finds that at least 20% of all cepheids have early-type companions. In a random survey of cepheids in the Large Magellanic Clouds, McNamara and Feltz (1980) have found that at least 14% of the cepheids have companions.

Although the frequency of binaries among the cepheid variables is

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of interest, the physical properties of the companions themselves should provide information on the masses and ages of the cepheids; information that at present is supplied only by theory.

McNamara and Feltz (1980) have recently completed a *uvby*β photometric investigation of 100 cepheids in the northern and southern sky. Several of these cepheids have c_1, m_1, and $(b-y)$ values at light minima that are obviously distorted by the presence of B-type companions. We have utilized our photometry to determine the color indices $(c_1)_0$ of the B stars, magnitude differences ($\Delta V = \Delta y$) between the companions and variables, and color excesses $E(b-y)$. The method employed assumes that anomalous c_1 and m_1 values at light minimum signal the presence of a companion. By adopting standard color indices of the cepheid, and assuming they are identical to a normal cepheid of similar period and amplitude, the color or spectral type of the B star distorting the color indices can be inferred. Intrinsic $(b-y)$, c_1, and m_1 values are available for B-type stars. For each choice of $(b-y)$ there will correspond a certain cepheid-companion magnitude difference that will satisfy the observed $(b-y)$ value. Each choice of $(u-v)$ and $(v-b)$ of the B star will also lead to a unique magnitude difference. If we let the subscript *a* refer to the data of the cepheid with the companion, subscript *c* to its B-type companion, and *s* represent a "standard" cepheid, we find the magnitude differences, $\Delta y = y_a - y_c$, are given by the equations

$$(\Delta y)_{b-y} = -2.5 \log \left\{ \frac{10^{-0.4(b-y)_s} - 10^{-0.4(b-y)_a}}{10^{-0.4(b-y)_a} - 10^{-0.4(b-y)_c}} \right\} \quad (1)$$

$$(\Delta y)_{v-b} = -2.5 \log \left\{ \frac{10^{-0.4[(m_1)_s + 2(b-y)_s]} - 10^{-0.4[(m_1)_a + (b-y)_a + (b-y)_s]}}{10^{-0.4[(m_1)_a + (b-y)_a + (b-y)_c]} - 10^{-0.4[(m_1)_c + 2(b-y)_c]}} \right\} , \quad (2)$$

$$(\Delta y)_{u-b} = -2.5 \log \left\{ \frac{10^{-0.4[c_1 + 2m_1 + 3(b-y)]_s} - 10^{-0.4[(c_1 + m_1 + (b-y))_a + (m_1 + 2(b-y))_s]}}{10^{-0.4[(c_1 + m_1 + (b-y))_a + (m_1 + 2(b-y))_c]} - 10^{-0.4[c_1 + 2m_1 + 3(b-y)]_c}} \right\} . \quad (3)$$

Now for each individual set, $(b-y)$, m_1, c_1, corresponding to a given B-type spectral type, we will obtain three values of Δy, one for each of equations (1), (2), and (3), but for only one set will the Δy values be identical and this set defines both the magnitude difference and the color index ($(c_1)_0$ or the spectral type) of the companion star. The method is illustrated in Figure 1 for the cepheid AX Circini for which one finds $(c_1)_0 = 0.60$ for the companion (corresponding to a B7 star) and a magnitude difference of $1^m.6$. These values are primarily determined from equations (2) and (3) (marked m_1 and c_1 in the figure). Reddening is estimated from the $(b-y)$ value at light maximum and a final reddening value determined by changing the color excess until the curves marked $(b-y)$ (data calculated from eq. (1)) and m_1 intersect the c_1 curve at the same position. The position of intersection of the m_1 and c_1 curves does not depend too critically on the color excess. Our spectral type of B7 may be compared with B8 estimated from an objective-pris spectrogram (λ2400) taken on a Skylab mission (Parsons et al. 1976).

We have determined the spectral type, magnitude difference, ΔV, be-

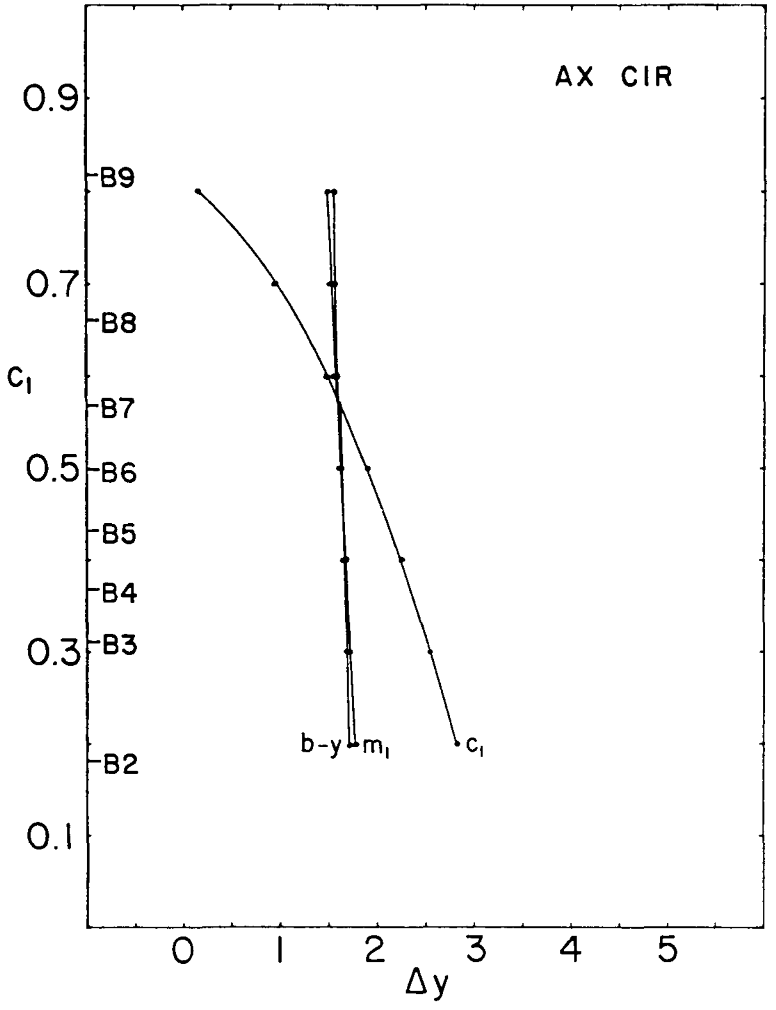

Fig. 1 - Determination of the spectral type of the companion of AX Cir and magnitude difference $\Delta y = \Delta v$ between the cepheid AX Cir and its companion.

tween the variable and B-type companion, and color excess of the system for the five stars listed in Table I by the method described in the previous paragraph. The absolute visual magnitude $\langle M_V \rangle_C$ (third column) of the variable is taken from the Sandage and Tammann (1968) period-luminosity relation (P-L). The magnitude differences ΔV (companion - variable) and intrinsic color indices are given in the fifth and sixth columns of Table I. The absolute magnitude of the companion $(M_V)_B$, listed in the seventh column has been calculated by adding the magnitude difference ΔV to the $\langle M_V \rangle$ value of the cepheid and applying a small correction to allow for the fact that the magnitude difference was usually determined near

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TABLE I

Properties of the Cepheids and B-Type Companions

Cepheids	log P	$\langle M_V \rangle_C$	$E(b-y)$	ΔV	$(c_1)_B$	$(M_V)_B$*	$(Sp)_B$	log T_C	$(M/M_\odot)_B$	$(M/M_\odot)_C$
SU Cyg	0.58	-3.0	0.08	2.3	0.56	-0.4	B7	8.13	3.6	5.2
AX Cir	0.72	-3.5	0.18	1.6	0.58	-1.7	B7	8.01	4.6	5.9
AW Per	0.81	-3.7	0.44	1.7	0.65	-1.9	B7.5	8.00	4.6	6.3
u Aql	0.85	-3.8	0.33	3.1	0.80	-0.2	B8	8.34	3.0	6.3
KN Cen	1.53	-5.7	0.65	2.1	0.07	-3.2	B2	7.33	9.0	10.4

*The $(M_V)_B$ value of the companion has been calculated from the $\langle M_V \rangle_C$ value of the cepheid and the ΔV value with an additional small correction applied to reduce the cepheids' M_V values to light minimum or the M_V values for the phase when ΔV was computed.

minimum light or at a phase different than mean light.

A plot of the position of both the cepheids and their companions in a color-magnitude diagram is given in Figure 2. We note that all of the B-type companions fall very close to or above the main sequence. The fact that none fall below the main sequence gives us confidence in our photometry and the method used to calculate the properties of the B star.

If we now assume that the B-star companion and cepheid were formed simultaneously a period-age relation for the cepheids can be determined from a knowledge of the age of the B star. We have plotted the data for the companions in the log $L/L_\odot, T_{eff}$ diagram (Iben 1967). The ages of the B stars can be estimated from the evolutionary tracks and ages indicated in the diagram. These evolutionary tracks are computed for stars with a composition of $X = 0.708$, $Y = 0.272$, and $Z = 0.020$. The ages of the B companions and consequently the ages of the cepheids determined by this method are listed in the ninth column of Table I. The ages are plotted against their periods in Figure 3. If we do not consider U Aquilae since the data are poor because ΔV is large, we find the age is related to the period through the relation

$$\log T_C = 8.60 - 0.83 \log P \quad , \tag{4}$$

(line in Fig. 3). This expression may be compared with the theoretical expression

$$\log T_C = 8.45 - 0.78 \log P \quad , \tag{5}$$

derived by Becker, Iben, and Tuggle (1977) from theoretical cepheid models with $Z = 0.02$ and $Y = 0.28$, or the expression

$$\log T_C = 8.16 - 0.68 \log P \quad , \tag{6}$$

derived by Efremov (1978) from cepheids in star clusters. T_C is the age of the cepheid in years and P is the period in days. The agreement of equation (4) with the theoretical expression (5) is good but perhaps not

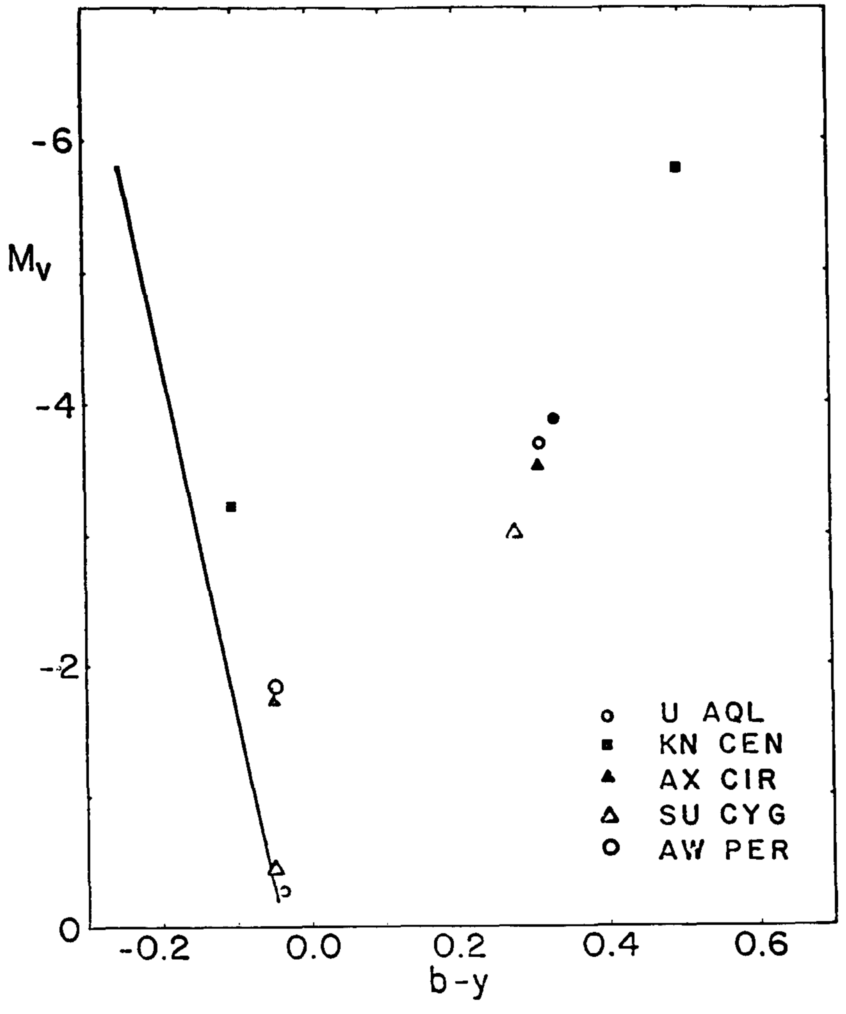

Fig. 2 - The position of the cepheids and their companions in the color-magnitude diagram. The solid curve is the main sequence. The cepheid and its companion are plotted with the same symbol. Note that the companions tend to lie above the main-sequence line for the most part.

surprising in view of the fact that the ages of cepheids are only 10% - 25% greater than main-sequence lifetimes of B stars. It is obvious that the slope of our equation could be improved by photometry of other long-period cepheids with companions. One promising star is HV 883 ($P = 134^d$) in the Large Magellanic Cloud which apparently has an ∿ B0 companion.

The masses of the B companions inferred from the position of the

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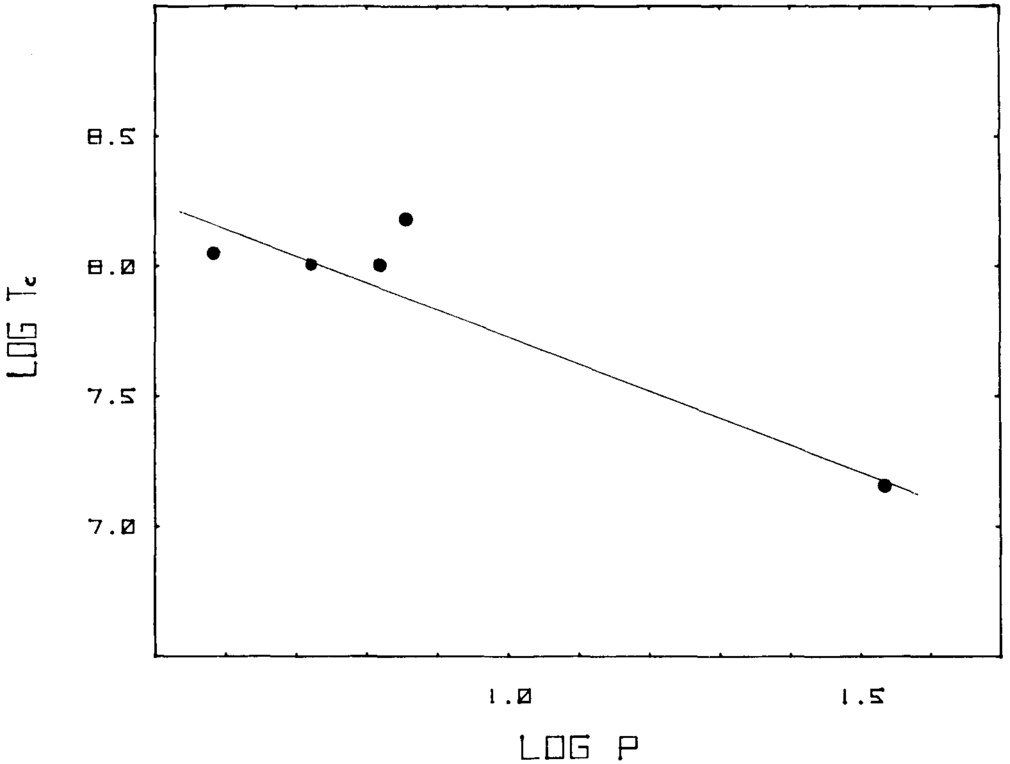

Fig. 3 - The period-age relation of cepheids. The equation of the line is log T_c = 8.60 - 0.83 log P.

stars in the log $L/L_\odot$,log T_{eff} diagram (Iben 1967) are listed in the tenth column of Table I. These values are of interest because the initial main-sequence masses of the variables should exceed these values as well as their present masses if no mass loss has occurred during their lifetimes. The B-star masses may be compared with the masses of the cepheids (last column) calculated from the equation

$$\log (L/L_\odot) = 0.46 + 3.68 \log M \qquad (7)$$

given by Becker, Iben, and Tuggle (1977) derived from cepheid models (second crossing of the instability strip) for stars with a composition Z_0 = 0.02 and Y_0 = 0.28. Surface gravities of cepheids (log g = 1.4 - 2.2) estimated from plots of intrinsic $(b-y)$ and c_1 values of the variables plotted in theoretical $(b-y)$,c_1 diagrams (model atmosphere) are consistent with surface gravities calculated from the theoretical-model masses and observed radii. There is no evidence of any large mass loss.

It is very evident that additional progress can be made by investigating the properties of B-type companions of cepheids in the UV where the flux of the B stars completely dominates the radiation emitted by the two stars. If both the spectral type and luminosity class of the B stars could be inferred from the UV spectrum, the absolute magnitudes of the cepheids could be calculated with the ΔV values given in Table I. This would provide a valuable check on the P-L relation.

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DISCUSSION

IBEN: I'm surprised that you find no significant difference between pulsation masses and evolutionari masses when you use the Sandage - Tamman P-L relationship. BIT had to assume that the S-T distance scale (set by the S-T PL relationship) was an underestimate by 0.25 mag. Otherwise $M_{puls} \sim 0.6\, M_{ev}$.

McNAMARA: My point is that surface temperatures assigned to the Cepheids under discussion have been underestimated by $\gtrsim$ 0.03. This goes a long way toward removing the erstwhile mass discrepancy.